EMTP-compatible transformer modeling for network interaction studies

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Background

- Overvoltage studies in power systems normally performed using EMTP tools (ElectroMagnetic Transients Programs)
  - EMTP-rv
  - PSCAD
  - ATP

- EMTP tools do not include wide-band, transformer models:
  - Accurate for low frequencies

- Not suitable for simulation of high-frequency transformer-network interactions.

Scope

- Terminal equivalent model suitable for high-frequency transformer network interaction studies
  - Linear effects only

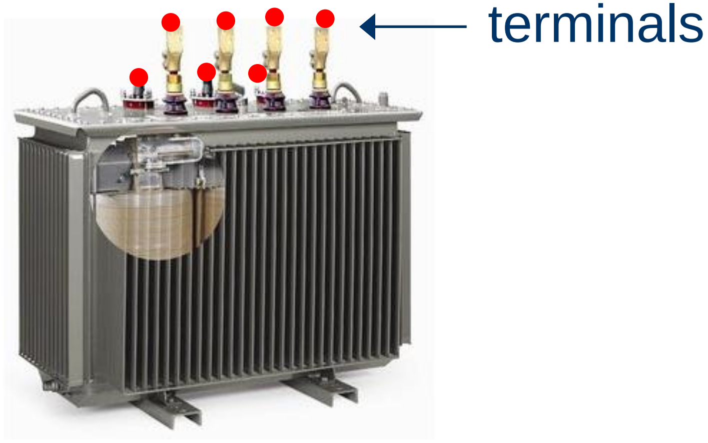
- Interfacing the model with EMTP-type tools

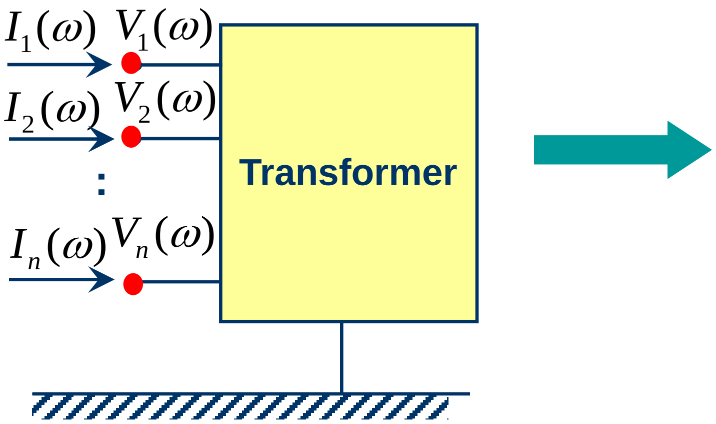
- Input data
  - Frequency sweep measurements, or
  - Manufacturer's white-box model parameters

- Examples

Part I:
Transformer Terminal Equivalent Model

Terminal admittance matrix



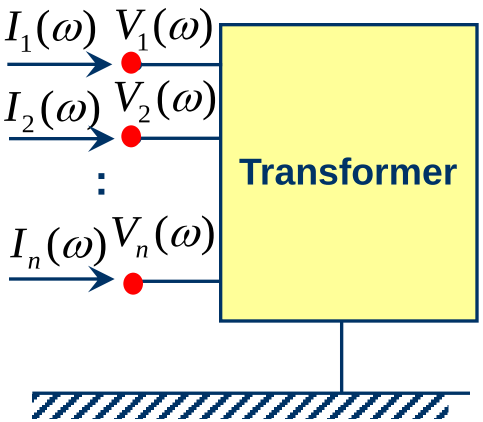


$$\mathbf{i}(\omega) = \mathbf{Y}(\omega)\mathbf{v}(\omega)$$

$$\begin{bmatrix} I_1(\omega) \\ I_2(\omega) \\ \vdots \\ I_n(\omega) \end{bmatrix} = \begin{bmatrix} Y_{11}(\omega) & Y_{12}(\omega) & \cdots & Y_{1n}(\omega) \\ Y_{21}(\omega) & Y_{22}(\omega) & & Y_{11}(\omega) \\ \vdots & & & \vdots \\ Y_{n1}(\omega) & Y_{n2}(\omega) & \cdots & Y_{nn}(\omega) \end{bmatrix} \begin{bmatrix} V_1(\omega) \\ V_2(\omega) \\ \vdots \\ V_n(\omega) \end{bmatrix}$$

Y(ω): From measurements or calculations

Modeling via rational functions


$I_1(\omega)$ $V_1(\omega)$
$I_2(\omega)$ $V_2(\omega)$
:
$I_n(\omega)$ $V_n(\omega)$
Transformer

$$\begin{bmatrix} I_1(\omega) \\ I_2(\omega) \\ \vdots \\ I_n(\omega) \end{bmatrix} = \underbrace{\begin{bmatrix} Y_{11}(\omega) & Y_{12}(\omega) & \cdots & Y_{1n}(\omega) \\ Y_{21}(\omega) & Y_{22}(\omega) & & Y_{11}(\omega) \\ \vdots & & & \vdots \\ Y_{n1}(\omega) & Y_{n2}(\omega) & \cdots & Y_{nn}(\omega) \end{bmatrix}}_{\mathrm{Y_n}} \begin{bmatrix} V_1(\omega) \\ V_2(\omega) \\ \vdots \\ V_n(\omega) \end{bmatrix}$$

Model extraction

Pole-residue model

$$\mathbf{Y}(\omega) \cong \sum_{m=1}^{N} \frac{\mathbf{R}_m}{j\omega - a_m} + \mathbf{D}$$

Vector Fitting

- Method for fitting a pole-residue model to frequency data

$$\mathbf{Y}(\omega) \cong \sum_{m=1}^{N} \frac{\mathbf{R}_m}{j\omega - a_m} + \mathbf{D}$$

  - Robust, efficient, accurate
  - Guaranteed stable poles
  - Symmetrical model

- Freely available on internet as Matlab function

**B. Gustavsen and A. Semlyen,"Rational approximation of frequency domain responses by vector fitting", IEEE Trans. Power Delivery, July 1999.*

Passivity

- The model extracted by VF is not necessarily passive
- Loss of passivity often leads to unstable time domain simulations

Passivity enforcement

$$\mathbf{Y}(\omega) = \sum_{m=1}^{N} \frac{\mathbf{R}_m}{j\omega - a_m} + \mathbf{D}$$

- Perturb model's parameters so that the model becomes passive*
  - Perturb elements in {**R**$_m$},**D**
  - make change to **Y**(s) minimal

$$\left.\begin{array}{l} \Delta\mathbf{Y} = \displaystyle\sum_{m=1}^{N} \frac{\Delta\mathbf{R}_m}{j\omega - a_m} + \Delta\mathbf{D} \cong \mathbf{0} \\ eig(\mathrm{Re}\{\mathbf{Y} + \displaystyle\sum_{m=1}^{N} \frac{\Delta\mathbf{R}_m}{j\omega - a_m}\}) > \mathbf{0} \\ eig(\mathbf{D} + \Delta\mathbf{D}) > \mathbf{0} \end{array}\right\} \Rightarrow \left.\begin{array}{l} \mathbf{A}_{sys}\,\Delta\mathbf{x} \cong 0 \\ \mathbf{B}_{sys}\,\Delta\mathbf{x} < \mathbf{c} \end{array}\right\}$$

Constrained LS
(e.g. QP)

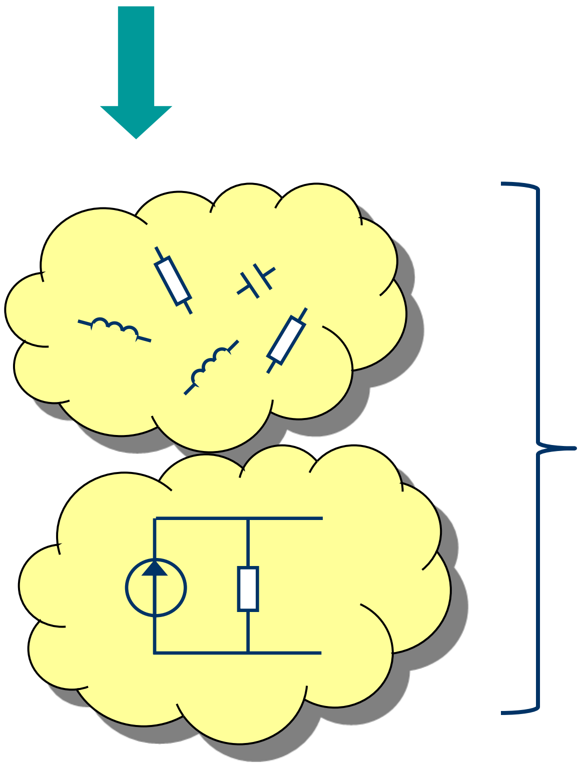
Δx: elements of {Δ**R**$_m$}, Δ**D**

*B. Gustavsen, and A. Semlyen, *"Enforcing passivity for admittance matrices approximated by rational functions", IEEE Trans. Power Systems, vol. 16, no. 1, pp. 97-104, Feb. 2001.*

Part II:
Interfacing the model with EMTP tools

Including model in EMTP type program

$$\mathbf{Y}(\omega) \cong \sum_{m=1}^{N} \frac{\mathbf{R}_m}{j\omega - a_m} + \mathbf{D} + s\mathbf{E}$$



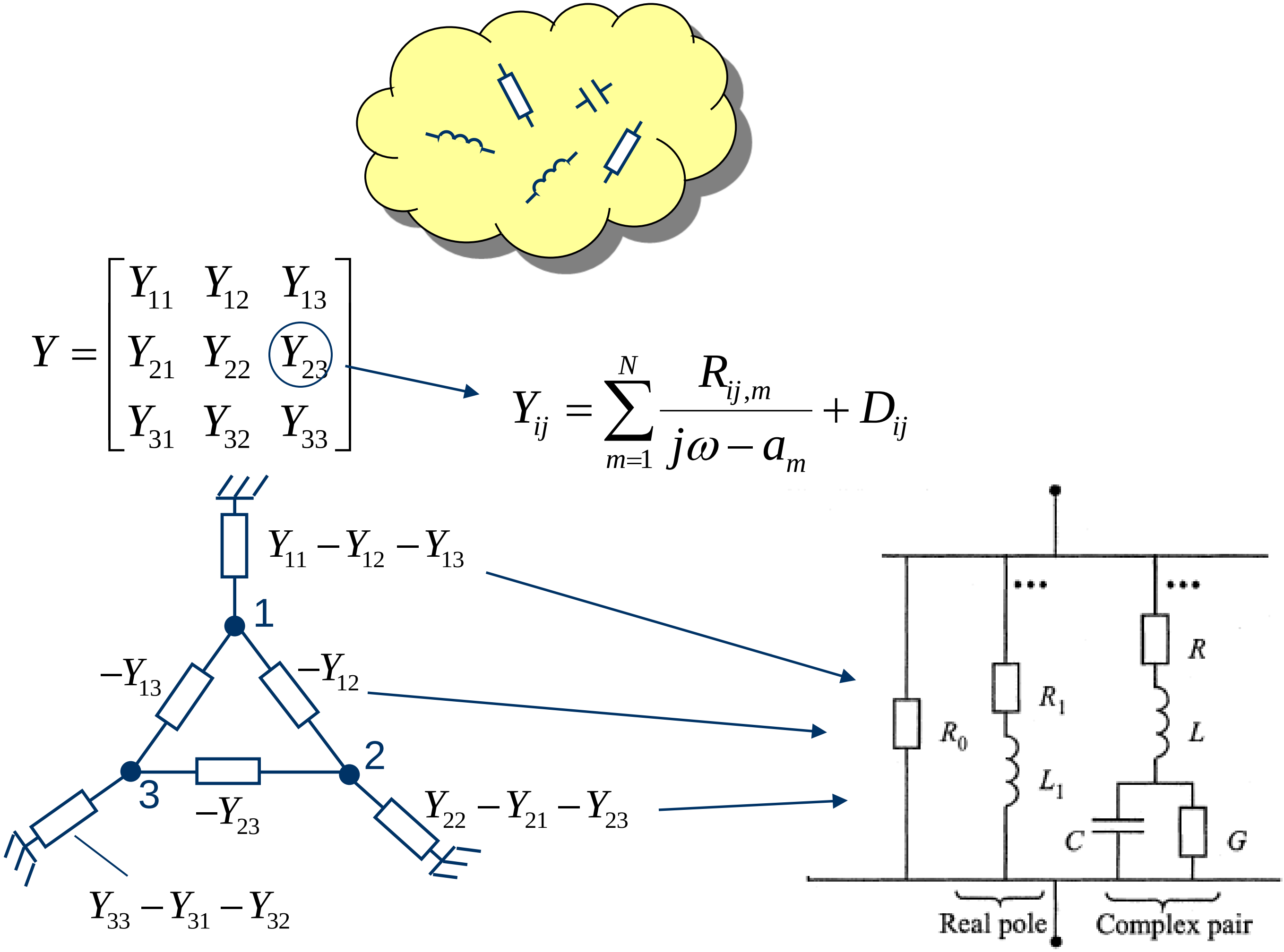
Lumped circuit equivalent

or

Norton equivalent w/ controlled source

EMTP time domain simulation

1. Lumped circuit equivalent



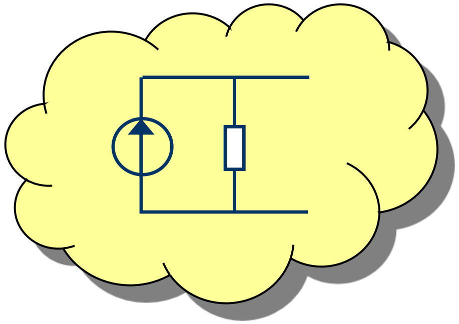
$$Y = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix}$$

$$Y_{ij} = \sum_{m=1}^{N} \frac{R_{ij,m}}{j\omega - a_m} + D_{ij}$$

$Y_{11} - Y_{12} - Y_{13}$
1
$-Y_{13}$
$-Y_{12}$
2
3
$-Y_{23}$
$Y_{22} - Y_{21} - Y_{23}$
$Y_{33} - Y_{31} - Y_{32}$
R_0
R_1
L_1
R
L
C
G
Real pole
Complex pair

EMTP branch cards

2. Norton equivalent w/ controlled source



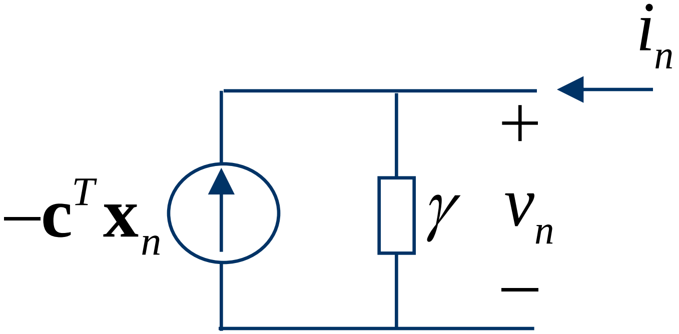
$$y(\omega)=\sum_{m}\frac{r_m}{j\omega-a_m} \quad\longrightarrow\quad y(t)=\sum_{m} r_m e^{at}$$

- Recursive convolution in time domain (fast!)

$$i(t)=y(t)*v(t) \quad\xrightarrow[\text{Trapezoidal integration}]{}\quad \begin{cases} \mathbf{x}_n=\boldsymbol{\alpha}\,\mathbf{x}_{n-1}+v_{n-1} \\ i_n=\mathbf{c}^T\mathbf{x}_n+\gamma\, v_n \end{cases}$$

$$\mathbf{x}_n = \boldsymbol{\alpha}\,\mathbf{x}_{n-1} + v_{n-1}$$

$$i_n = \mathbf{c}^T \mathbf{x}_n + \gamma\, v_n$$



EMTP compatibility

	ATP	PSCAD	EMTP-rv
RLC network	X	?	?
Norton equivalent	–	X*	X**

* User-defined component

** Convert to state-space block

Part III:
Model input data

Samples for the model identification

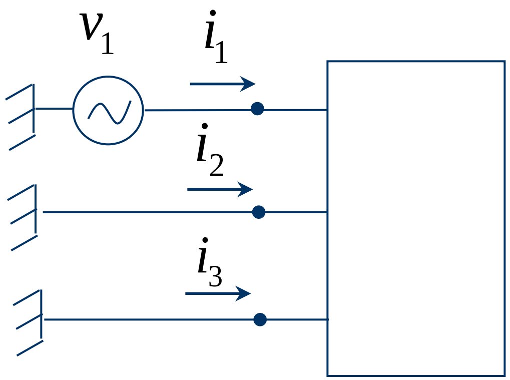
$$\mathbf{Y}(\omega) \approx \sum_m \frac{\mathbf{R}_m}{j\omega - a_m} + \mathbf{D} + s\mathbf{E}$$

- Frequency sweep measurements, or
- Calculations from manufacturer's white-box model

Calculating Y(ω) using frequency sweep measurements

Columnwise measurement of admittance matrix

Example: 3-terminal device



$$\begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} \\ Y_{21} & Y_{22} & Y_{23} \\ Y_{31} & Y_{32} & Y_{33} \end{bmatrix} \cdot \begin{bmatrix} v_1 \\ v_2 = 0 \\ v_3 = 0 \end{bmatrix}$$

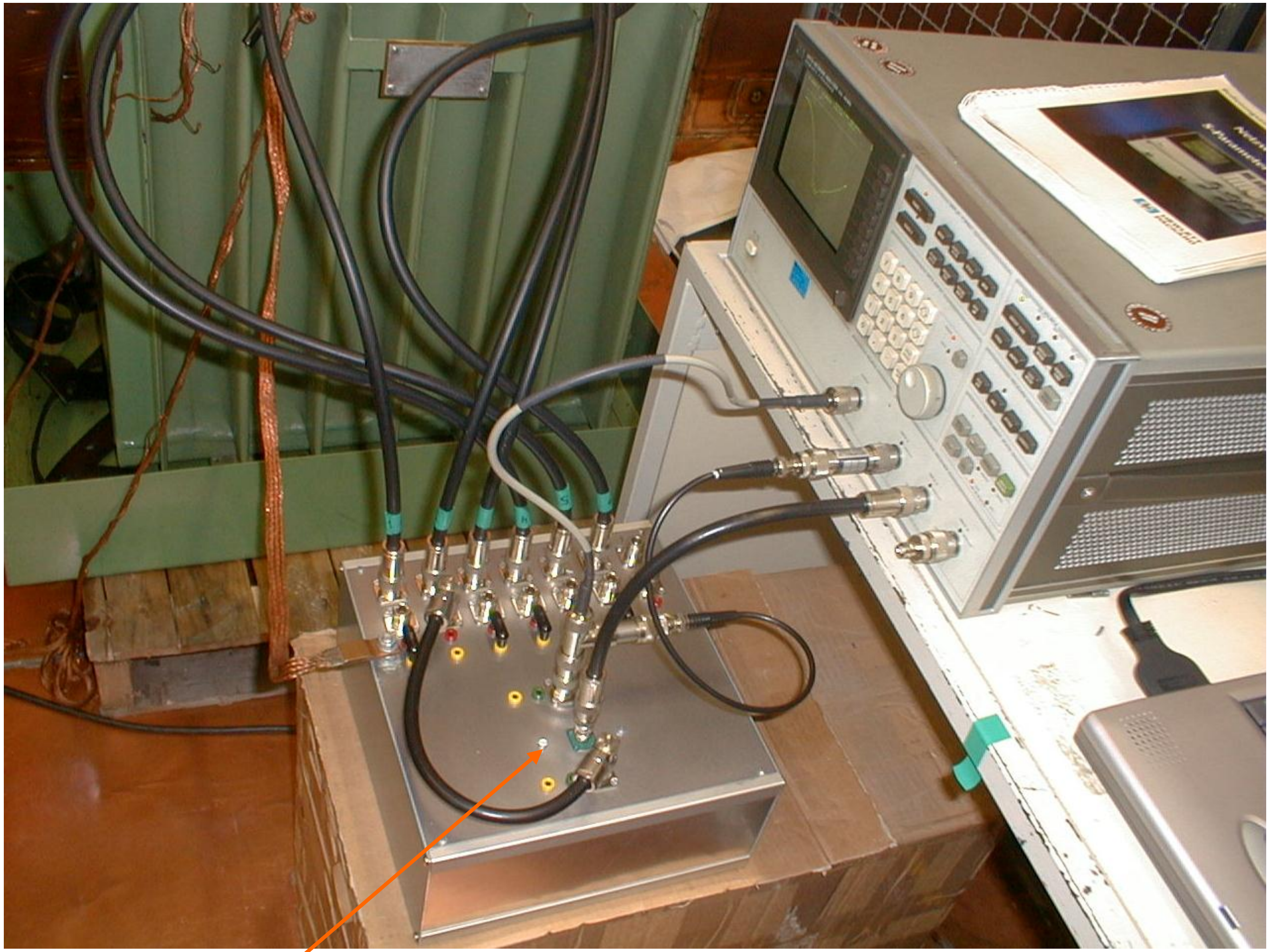
$$Y_{11} = i_1 / v_1$$

$$Y_{21} = i_2 / v_1$$

$$Y_{31} = i_3 / v_1$$

Frequency sweep measurements

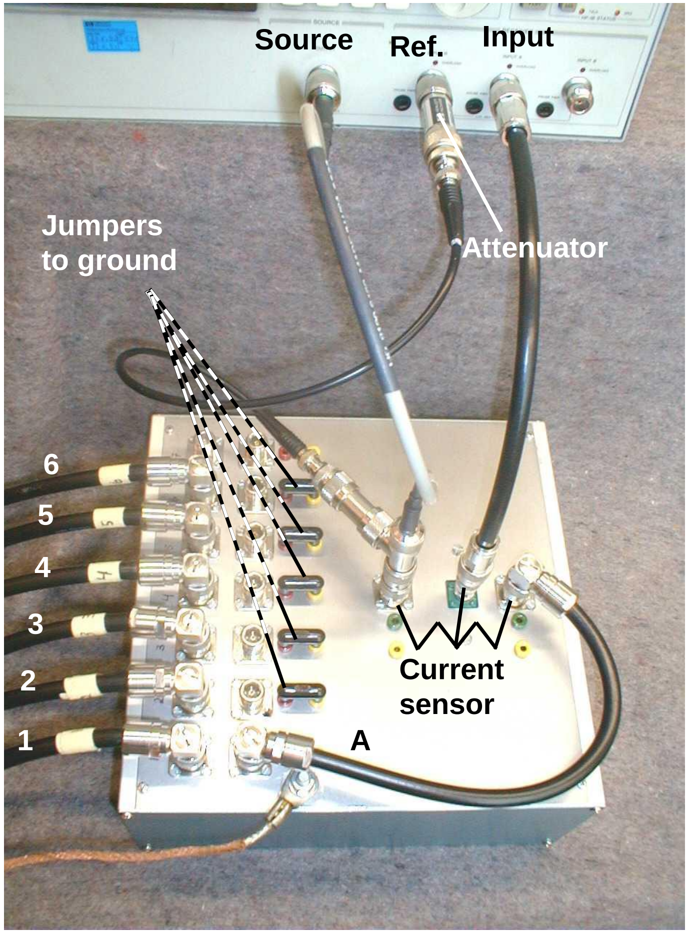
- Network analyzer
- Connection box
- Coaxial cables
- Current sensor



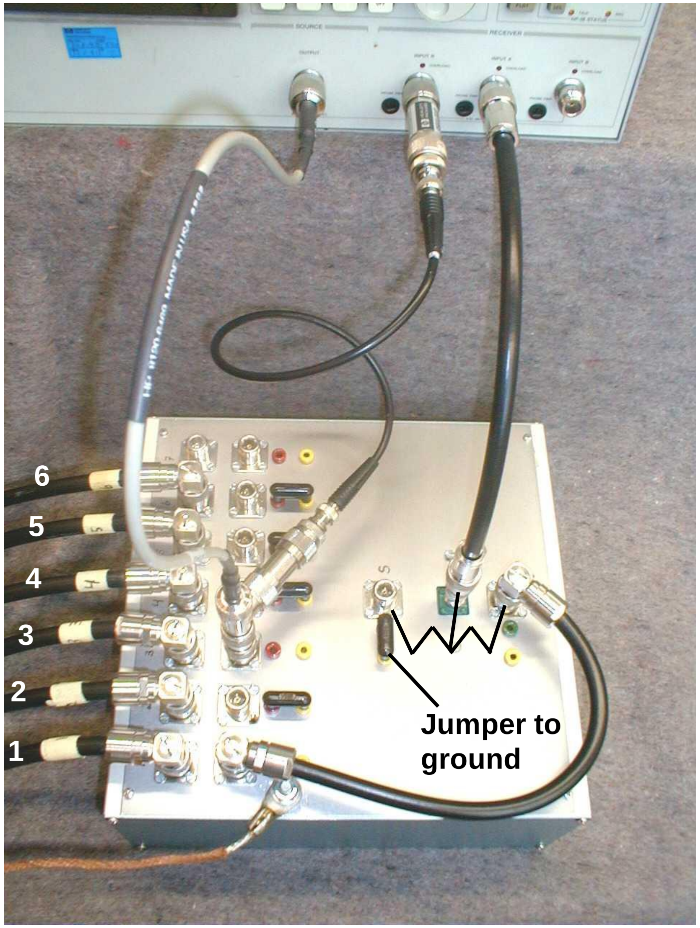
Built-in current sensor (Pearson)

Measurement setup (cont.)

Measuring $Y_{11} = i_1 / v_1$



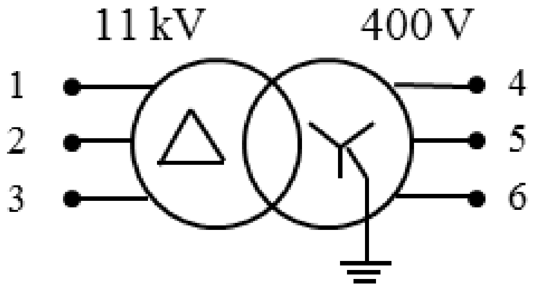
Measuring $Y_{13} = i_1 / v_3$



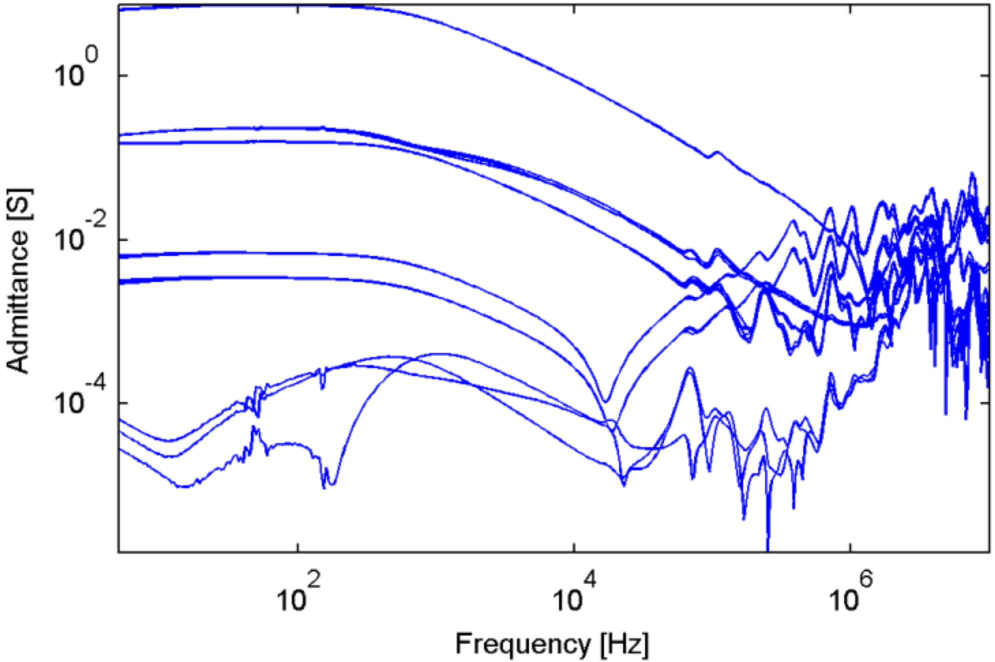
Measurement of Y (5 Hz – 10 MHz)

$$\begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ i_4 \\ i_5 \\ i_6 \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & Y_{13} & Y_{14} & Y_{15} & Y_{16} \\ Y_{21} & Y_{22} & Y_{23} & Y_{24} & Y_{25} & Y_{26} \\ Y_{31} & Y_{32} & Y_{33} & Y_{34} & Y_{35} & Y_{36} \\ Y_{41} & Y_{42} & Y_{43} & Y_{44} & Y_{45} & Y_{46} \\ Y_{51} & Y_{52} & Y_{53} & Y_{45} & Y_{55} & Y_{56} \\ Y_{61} & Y_{62} & Y_{63} & Y_{46} & Y_{56} & Y_{66} \end{bmatrix} \cdot \begin{bmatrix} v_1 \\ v_2 \\ v_3 \\ v_4 \\ v_5 \\ v_6 \end{bmatrix}$$

300 kVA transformer



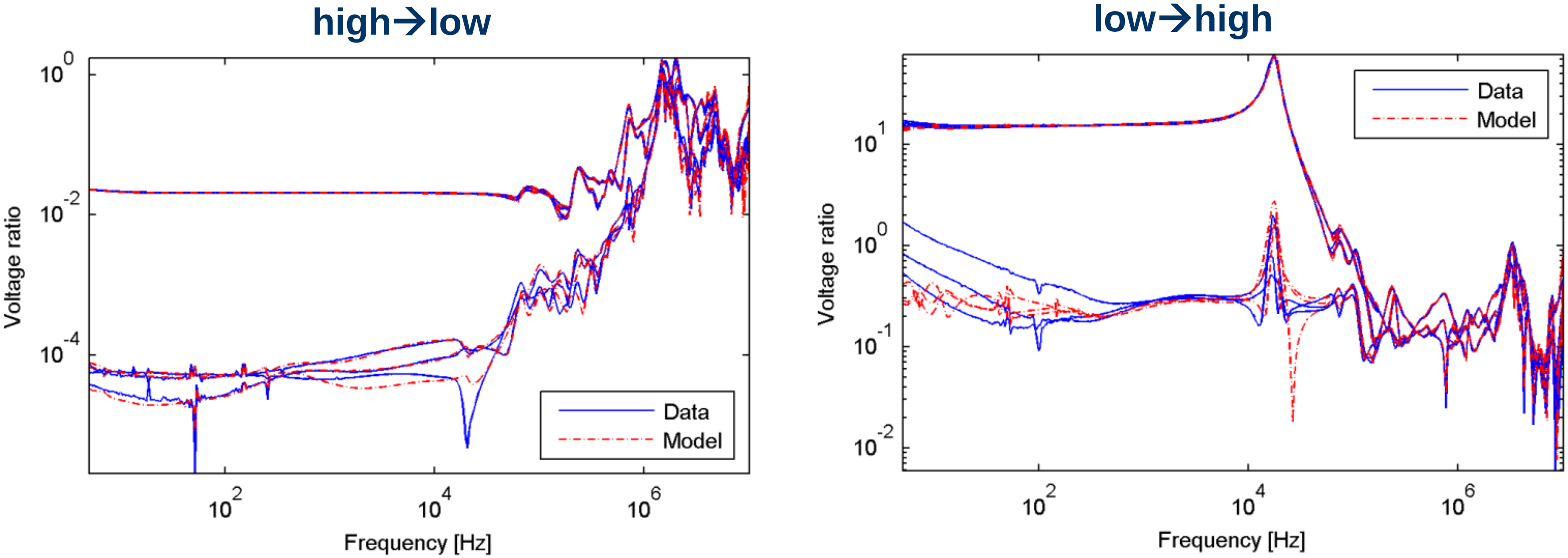
Elements of **Y**(ω)



Vector Fitting + Passivity Enf.

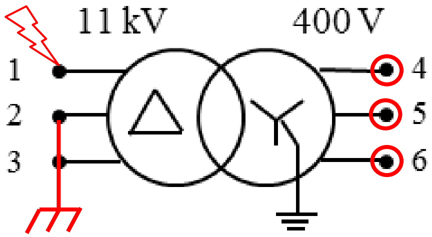
$$\mathbf{Y}_{\text{model}}(\omega) \approx \sum_{m=1}^{100} \frac{\mathbf{R}_m}{j\omega - a_m} + \mathbf{D} + s\mathbf{E}$$

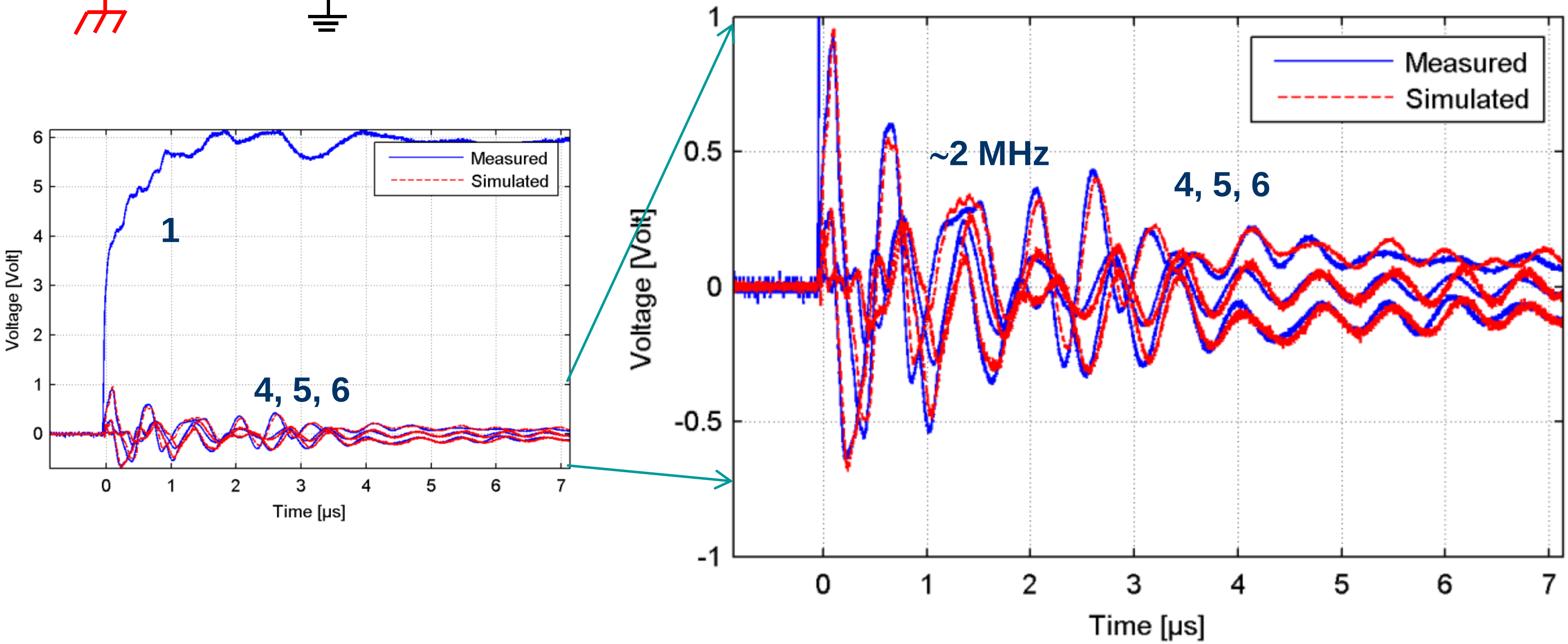
- Voltage ratios
  (computed from $\mathbf{Y}_{\text{data}}$ and $\mathbf{Y}_{\text{model}}$)

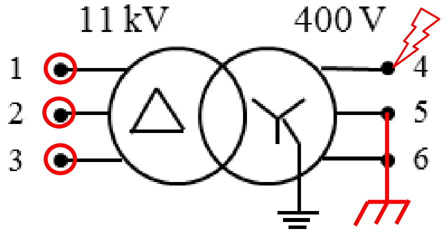


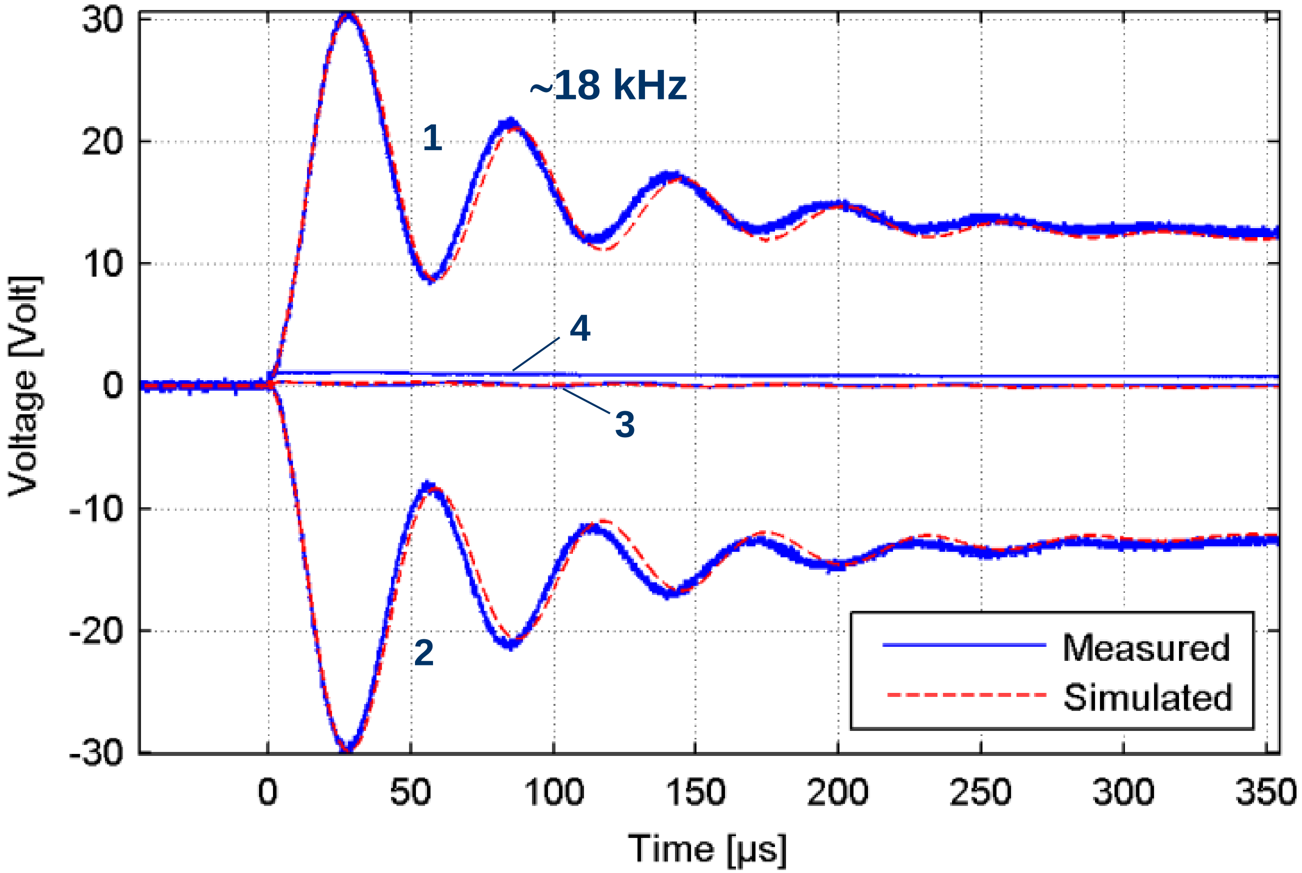
Time domain measurement & simulation

- Simulation method: Norton equivalent






11 kV
400 V
1
2
3
4
5
6

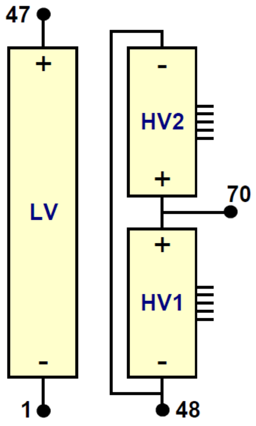

~18 kHz
1
4
3
2
Measured
Simulated
Voltage [Volt]
30
20
10
0
-10
-20
-30
0
50
100
150
200
250
300
350
Time [μs]

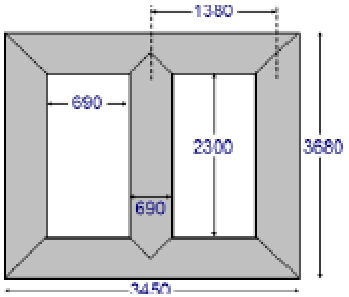
Alternative approach:

Calculating Y(ω) from manufacturer's white-box model paramretrs

Example

Fictitious transformer example used in CIGRE WG A2/C4.39 (courtesy: Alvaro Portillo)

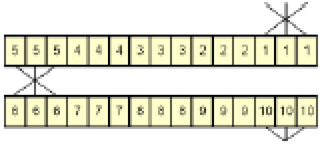




100 MVA unit, 230/69 kV, BIL=1050 kV

10.2.2.2 LV Winding – "Continuous Disk Type"

The low voltage winding is a conventional "Continuous Disk Type" with three conductors in parallel (Figure 10.3).



10.2.2.3 HV Winding – "Interleaved Disk Type"

The high voltage winding is a conventional "Interleaved Disk Type" (Figure 10.4).

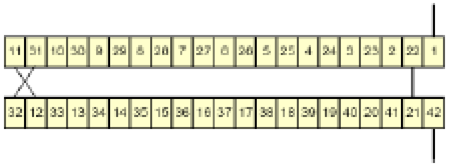
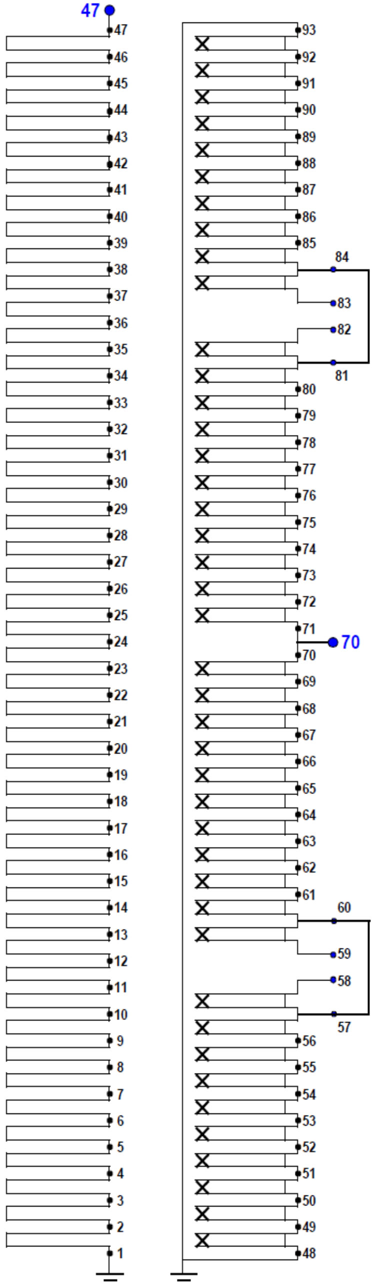


Figure 10.4

Winding discretization



White Box Model description

Lumped circuit parameter model, based on spatial discretzation of windings

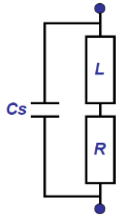
Matrices: **R**, **L**, **G**, **C**

Basic equations

$$\mathbf{i}_C = \mathbf{C}\dot{\mathbf{v}} \qquad \mathbf{e} = \mathbf{T}\mathbf{v}$$

$$\mathbf{i}_G = \mathbf{G}\mathbf{v} \qquad \mathbf{i}_L = \mathbf{T}^T\mathbf{i}$$

$$\mathbf{e} = \mathbf{L}\dot{\mathbf{i}} + \mathbf{R}\mathbf{i} \qquad \mathbf{i}_C + \mathbf{i}_L + \mathbf{i}_G = \mathbf{i}_S$$



L:
Mutual coupling beween all inductive branches

Calculate terminal admittance matrix w.r.t. external nodes

1. Calculate admittance matrix **Y**(*s*) to all nodes, at discrete freq.

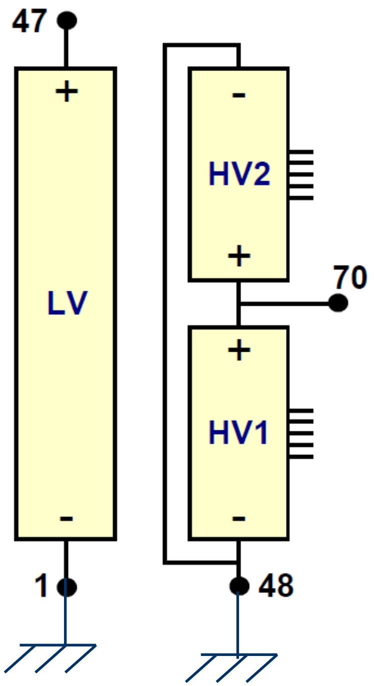
$$\mathbf{Y}(\omega_k) = [(\mathbf{G} + j\omega_k \mathbf{C}) + \mathbf{T}^T (\mathbf{R} + j\omega_k \mathbf{L})^{-1} \mathbf{T}], k = 1 \ldots K$$

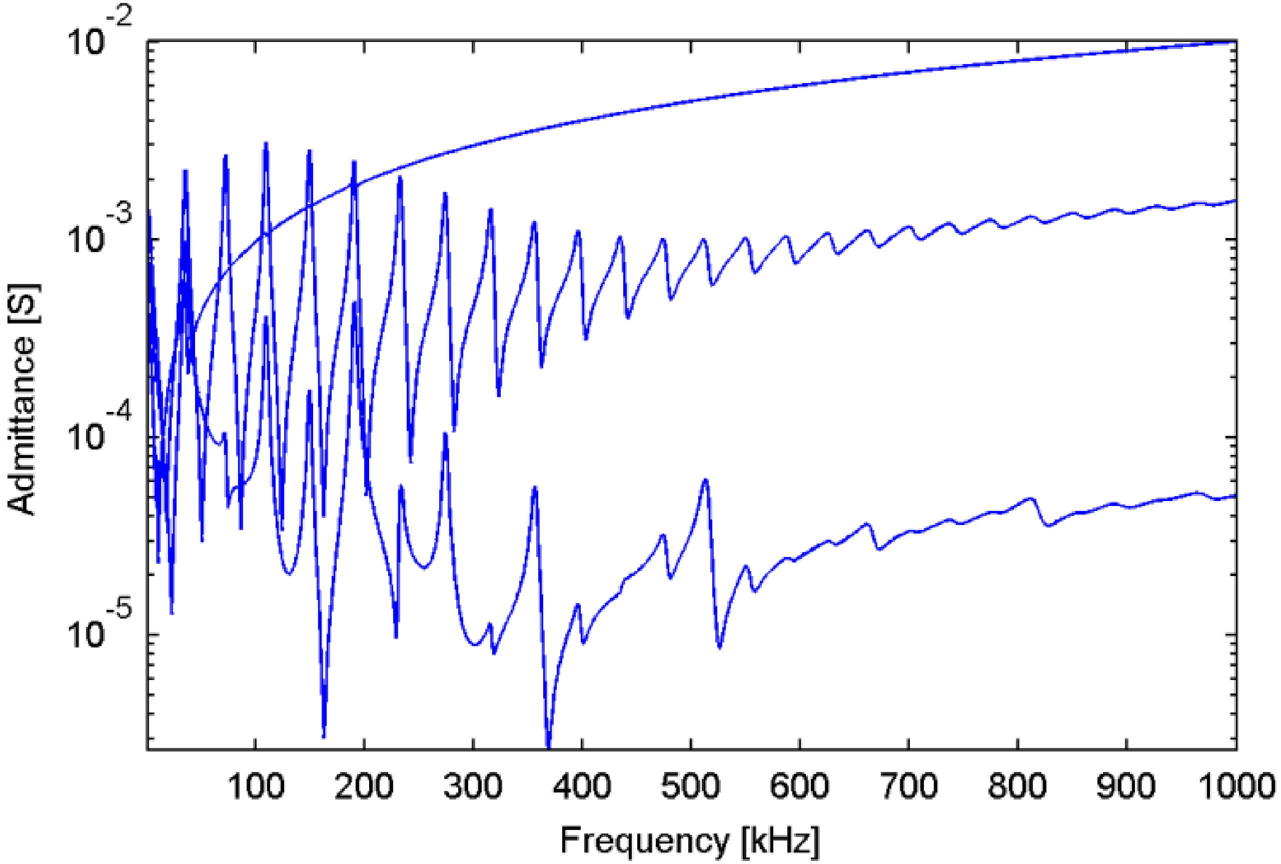
2. Introduce groundings and short circuits

3. Reduce model with respect to external terminals

$$\mathbf{Y}_{\mathrm{ext}}(j\omega_k)$$

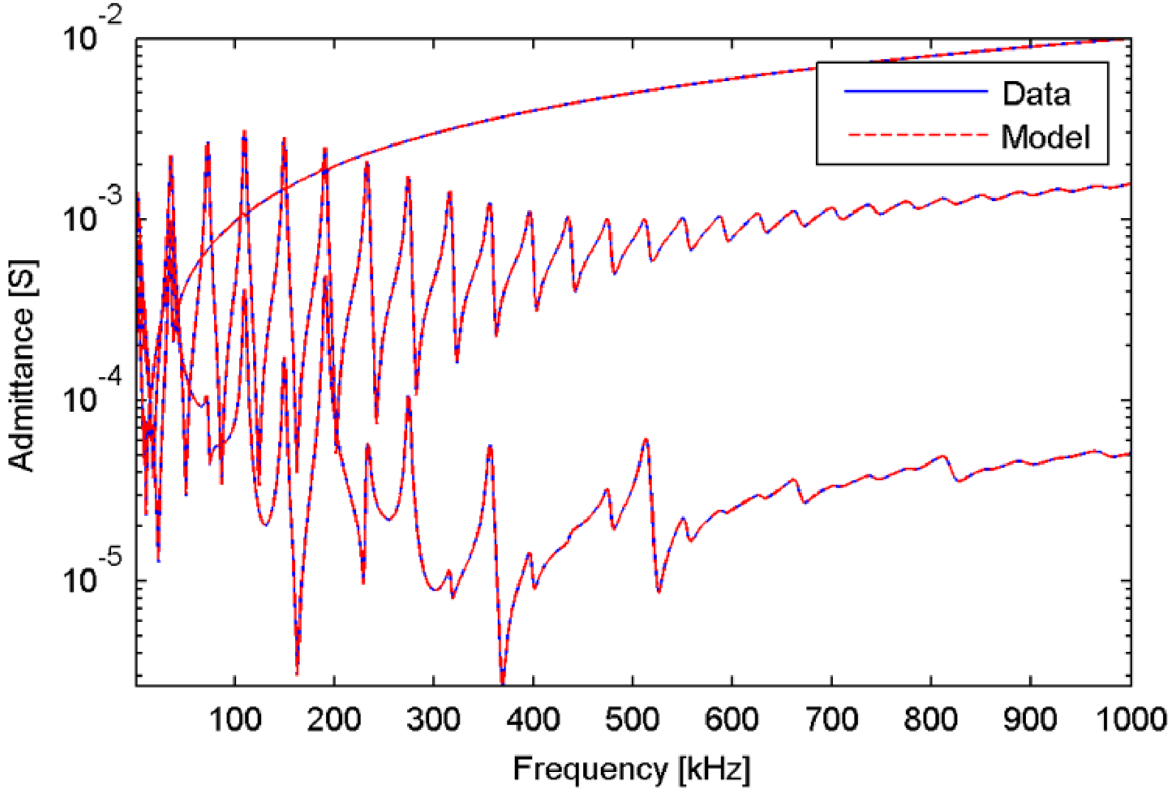
Admittance matrix w.r.t. terminals 47, 70





Modeling with rational functions

1. $\mathbf{Y}_{\mathrm{ext}}(\omega) \cong \sum_{m=1}^{N} \frac{\mathbf{R}_m}{j\omega - a_m} + \mathbf{D}$ Rational funcion approximation



N=80

The information about white-box parameters is hidden !

Internal voltages

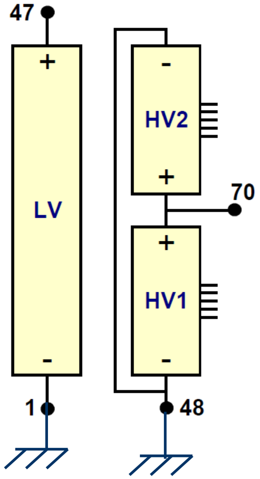
$$\begin{bmatrix} \mathbf{v}_{\mathrm{ext}} \\ \mathbf{v}_{\mathrm{int}} \end{bmatrix} = \begin{bmatrix} \mathbf{Z}_A & \mathbf{Z}_B \\ \mathbf{Z}_C & \mathbf{Z}_D \end{bmatrix} \begin{bmatrix} \mathbf{i}_{\mathrm{ext}} \\ \mathbf{i}_{\mathrm{int}} \end{bmatrix}$$

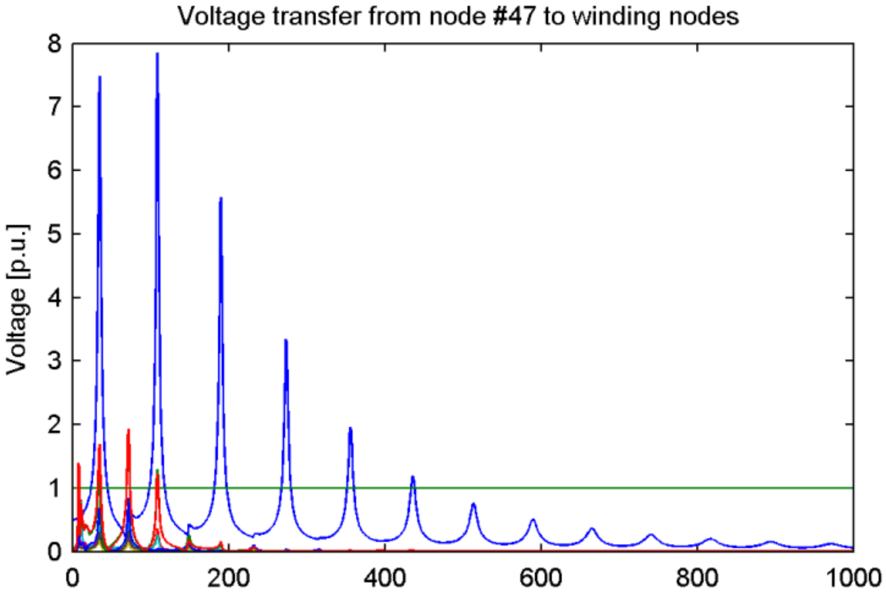
Calculate voltage transfer to internal node as

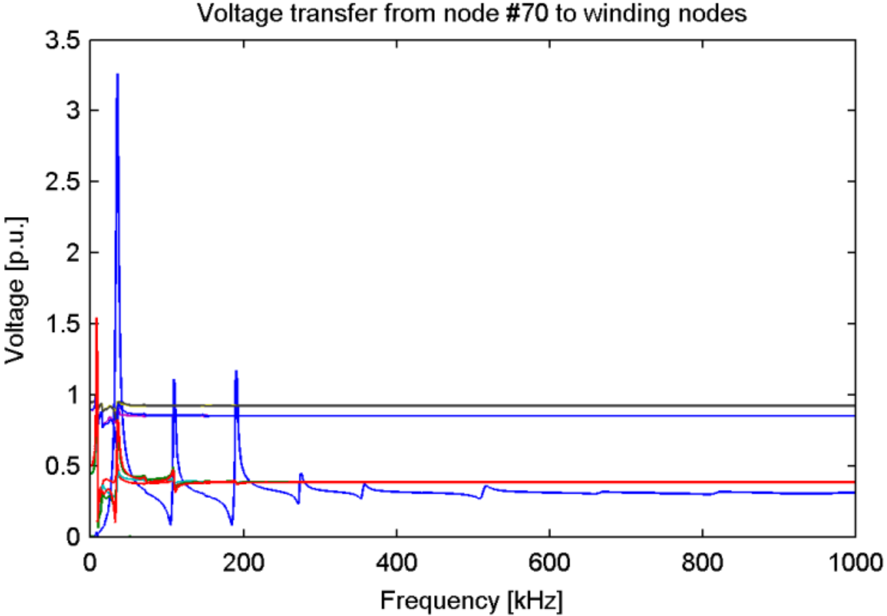
$$\mathbf{v}_{int}(\omega) = \mathbf{H}_{\mathrm{transfer}}(\omega)\mathbf{v}_{ext}(\omega)$$

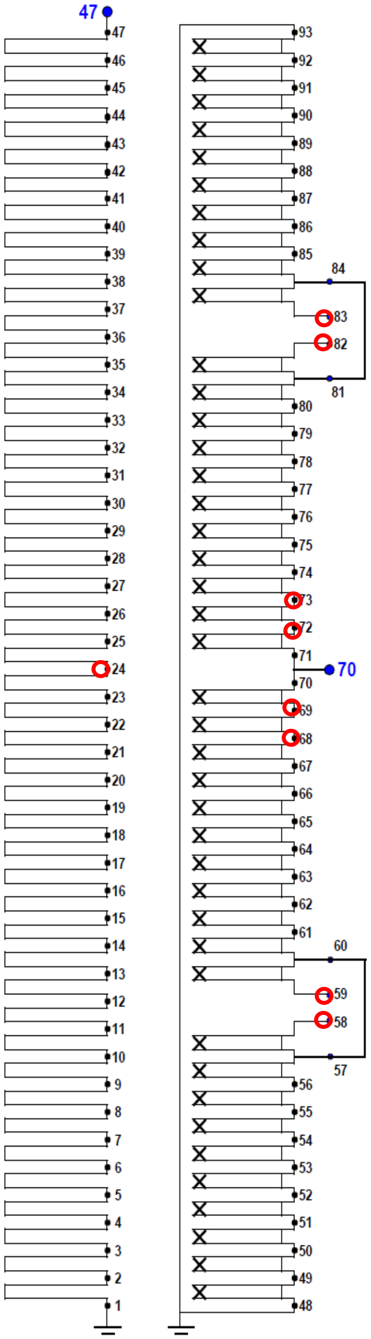
$$\mathbf{H}_{\mathrm{transfer}}(\omega) = \mathbf{Z}_C(\omega)\mathbf{Y}_{\mathrm{ext}}(\omega)$$

Voltage transfer from external nodes 47, 70 to internal nodes 24 47 58 59 68 69 72 73 82 83





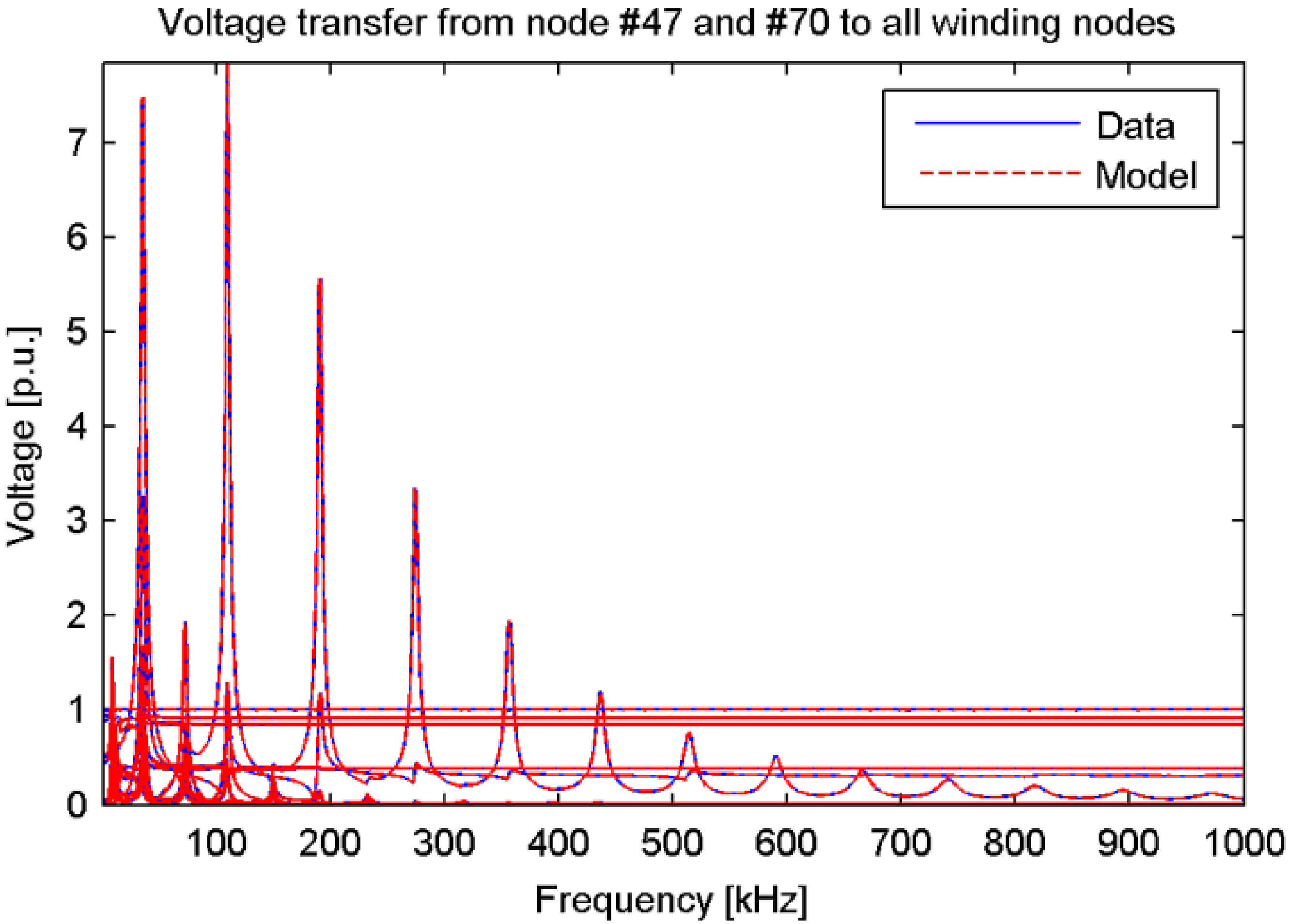




Modeling with rational functions

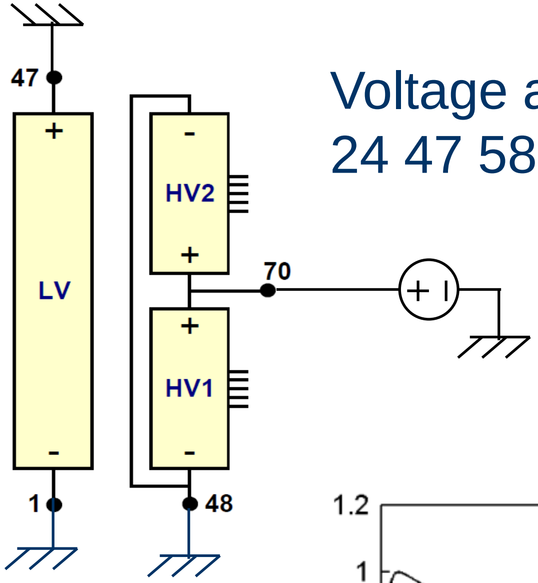
$$\mathbf{h}_i(s) \cong \sum_{m=1}^{N} \frac{\mathbf{r}_{i,m}}{s-a_m} + \mathbf{r}_{0,m} \quad , i = 1,2$$

Rational funcion approximation (Vector Fitting)



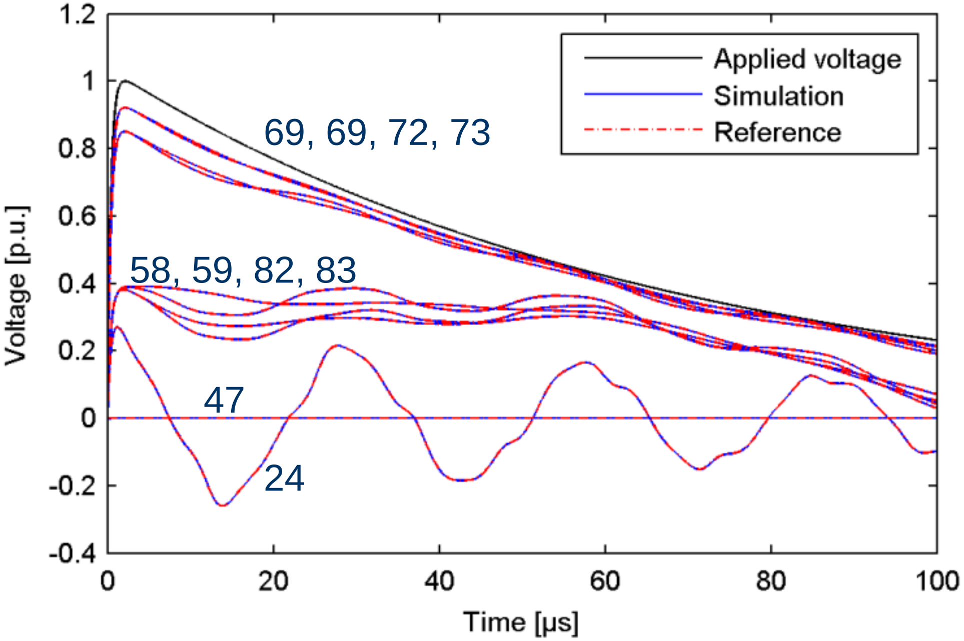
N=80
(per column)

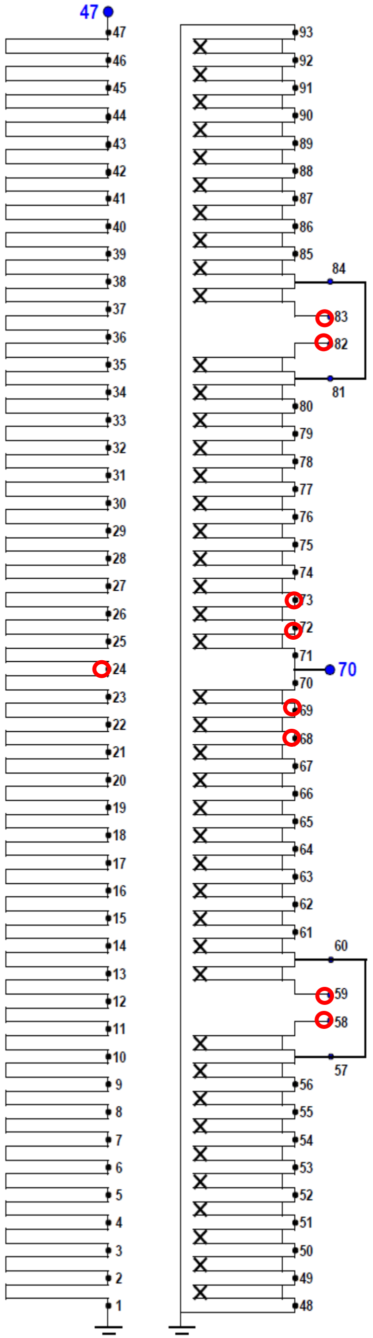
Time domain simulation



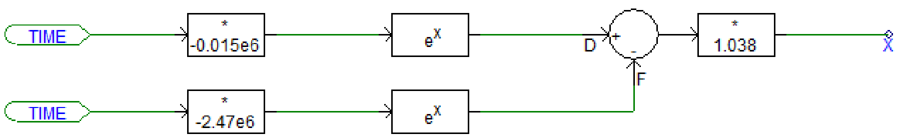
Voltage at internal nodes
24 47 58 59 68 69 72 73 82 83

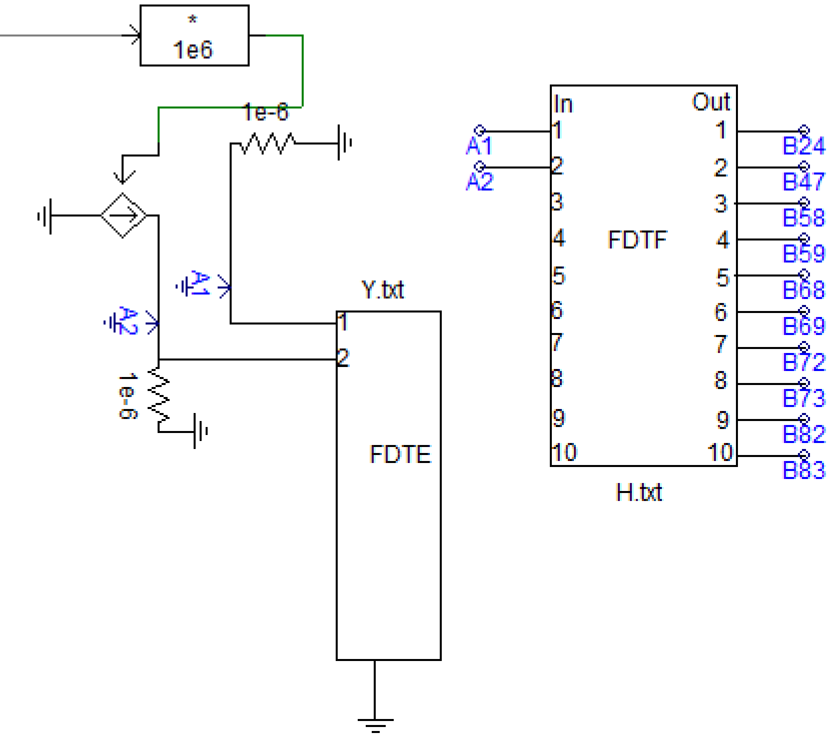
1.2/50 µs

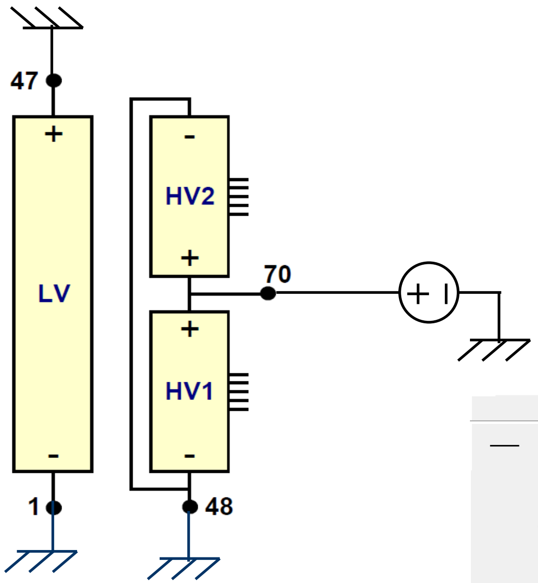


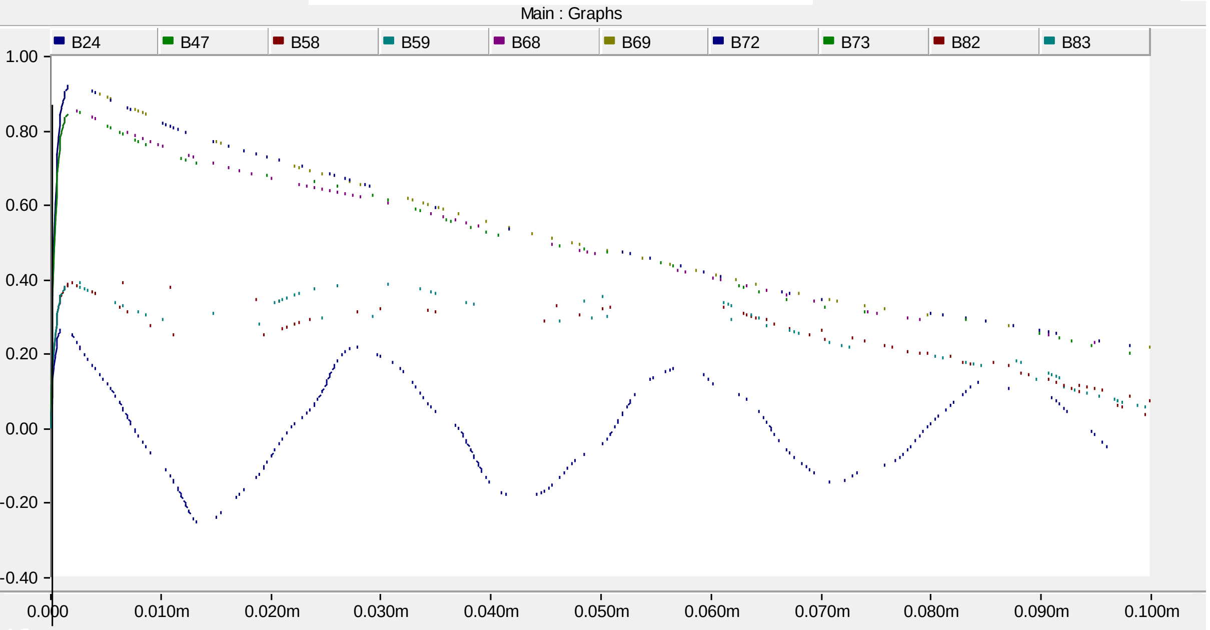


Simulation in PSCAD

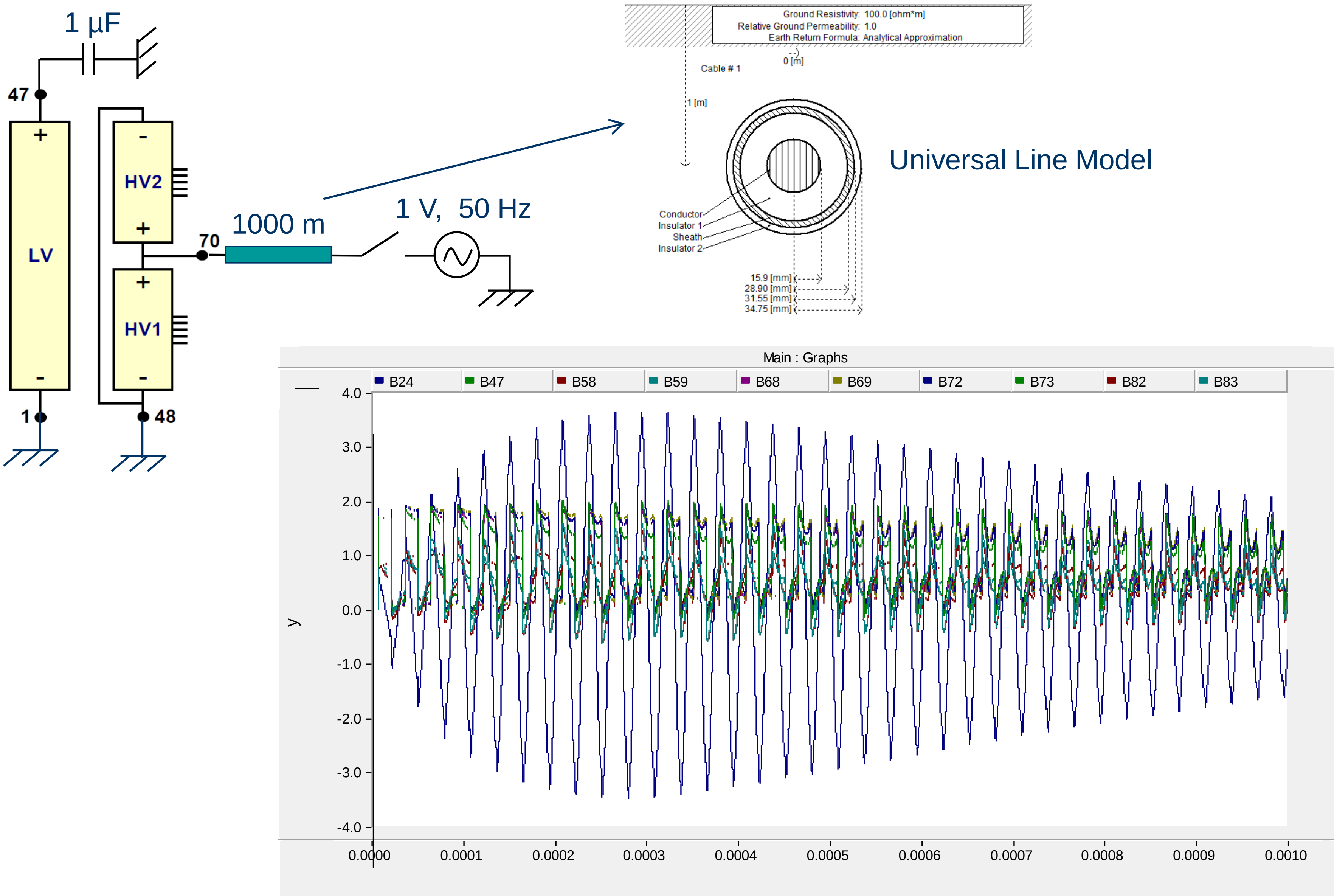








Network interaction study



Universal Line Model

Conclusions

- Transformer high-frequency behavior can be characterized by its terminal admittance matrix, $\mathbf{Y}(\omega)$

- $\mathbf{Y}(\omega)$ can be fitted with a pole-residue model to obtain an EMTP-compatible model
  - Lumped circuit equivalent, or
  - Norton equivalent (recursive convolution)

- $\mathbf{Y}(\omega)$ can be obtained from
  - Measurements, or
  - Manufacturer's white box model parameters